Why a ring of stars at $r = 20$ kpc?

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Abstract. The recently discovered ring of stars near Galactocentric distance $r = 20$ kpc is interpreted as baryonic matter accreted onto the second caustic ring of dark matter in our galaxy. Caustic rings of dark matter were predicted in the Galactic plane at radii $a_n \simeq 40$ kpc/n where $n = 1, 2, 3...$ They can reveal themselves by their gravitational influence on the distribution of baryonic matter. There is additional evidence for caustic rings of dark matter in the Milky Way from a series of sharp rises in the Galactic rotation curve. The positions of the rises are consistent at the 3% level with the above law for the caustic ring radii. Also, a triangular feature in the IRAS map of the galactic plane is consistent with the imprint of the caustic ring of dark matter nearest to us ($n = 5$) upon dust and gas in the Galactic plane. These observations imply that the dark matter in our neighborhood is dominated by a single flow whose density and velocity vector are estimated.

1 A Giant Stellar Ring in the Milky Way Plane

Recently the discovery was announced of what appears to be a ring of stars, with radius of order 20 kpc, circling the Galaxy [1,2,3]. I will not discuss the evidence for the alleged ring of stars, but merely assume that it exists. The existence of such a ring is puzzling. In ref. [1], the ring is interpreted as the tidal stream from an accreted satellite galaxy. However, in this interpretation it is hard to account for the fact that the star population is confined to a nearly circular region [2]. Also, it would be an accident that the tidal stream lies in the Galactic plane. Ibata et al. [2] propose instead that the ring of stars is a perturbation of the Galactic disk population. They do not however explain what causes the perturbation. I would like to propose that the perturbation that causes the ring of stars at $r = 20$ kpc is the gravitational field of a caustic ring of dark matter.

Several years ago caustic rings of dark matter were predicted in the Galactic plane at radii $a_n \simeq 40$ kpc/n where $n = 1, 2, 3, ..$ [4]. The ring of stars at $r = 20$ kpc may be baryonic matter accreted onto the $n = 2$ caustic ring of dark matter. This interpretation would account for both its radius and its location in the Galactic plane.

The existence of dark matter caustics in the halos of galaxies is a corollary of the observation [5] that cold dark matter particles lie on a three-dimensional sheet in six-dimensional phase-space. There are compelling reasons to believe that the dark matter of the universe is constituted in large part of non-baryonic collisionless particles with very small primordial velocity dispersion, such as axions and/or weakly interacting massive particles (WIMPs). Generically, such

particles are called cold dark matter (CDM). The primordial velocity dispersion of the leading cold dark matter candidates is extremely small, of order $10^{-12}c$ for WIMPs and $3 \cdot 10^{-17}c$ (at most) for axions. This means that, before the onset of structure formation, all the particles at a given location $\boldsymbol{x}$ have the same velocity $\boldsymbol{v}(\boldsymbol{x})$, i.e. the particles lie on a 3-dim. sheet in 6-dim. phase space. The thickness of the sheet is the velocity dispersion. Because the number of particles is huge (of order 10^{84} axions and/or 10^{68} WIMPs per galactic halo), the sheet is effectively continuous. It cannot break and hence its evolution is constrained by topology.

2 The Phase-Space Structure of Galactic Halos

Where a galaxy forms, the sheet wraps up in phase-space, turning clockwise in any two dimensional cut $(x, \dot{x})$ of that space. x is the physical space coordinate in an arbitrary direction and $\dot{x}$ its associated velocity. The outcome of this process is a discrete set of flows at any physical point in a galactic halo [5]. Two flows are associated with particles falling through the galaxy for the first time ($n = 1$), two other flows are associated with particles falling through the galaxy for the second time ($n = 2$), and so on. Scattering in the gravitational wells of inhomogeneities in the galaxy (e.g. molecular clouds and globular clusters) are ineffective in thermalizing the flows with low values of n. Recently, Stiff and Widrow [6] have put these discrete flows, also called 'velocity peaks', into evidence in N-body simulations using a new technique which increases the resolution of the simulations in the relevant regions of phase-space.

A commonly raised objection to the above picture is that before the dark matter falls onto a large galaxy, such as our own, it has already clustered on smaller scales, making dwarf halos and other types of clumps, in a process called "hierarchical clustering". However, this is not a valid objection. The effect of hierarchical clustering is only to produce an effective velocity dispersion for the infalling dark matter, i.e. a thickening of the phase space sheet. This effective velocity dispersion is at most equal to the velocity dispersion, of order 10 km/s, of dwarf halos and on average should be much less than that. Because the effective velocity dispersion of the infalling dark matter is much less than the 300 km/s velocity dispersion of the Galaxy as a whole, the phase space sheet folds in qualitatively the same way as in the zero velocity dispersion case. The flows and caustics remain.

Caustics appear wherever the projection of the phase-space sheet onto physical space has a fold [4,7,8,9]. Generically, caustics are surfaces in physical space. On one side of the caustic surface there are two more flows than on the other. At the surface, the dark matter density is very large. It diverges there in the limit of zero velocity dispersion. There are two types of caustics in the halos of galaxies, inner and outer. The outer caustics are simple fold (A_2) catastrophes located on topological spheres surrounding the galaxy. They occur near where a given outflow reaches its furthest distance from the galactic center before falling back in. The inner caustics are rings [4]. They occur near where the particles

with the most angular momentum in a given inflow reach their distance of closest approach to the galactic center before going back out. A caustic ring is a closed tube whose cross-section is an *elliptic umbilic* (D_{-4}) catastrophe [7]. The existence of these caustics and their topological properties are independent of any assumptions of symmetry.

Primordial peculiar velocities are expected to be the same for baryonic and dark matter particles because they are caused by gravitational forces. Later the velocities of baryons and CDM differ because baryons collide with each other whereas CDM is collisionless. However, because angular momentum is conserved, the net angular momenta of the dark matter and baryonic components of a galaxy are aligned. Since the caustic rings are located near where the particles with the most angular momentum in a given infall are at their closest approach to the galactic center, they lie close to the galactic plane.

A specific proposal was made for the radii a_n of caustic rings [4]:

$$\{a_n : n = 1, 2, ...\} \simeq (39,\ 19.5,\ 13,\ 10,\ 8, ...)\text{kpc} \times \left(\frac{j_{\max}}{0.25}\right)\left(\frac{v_{\text{rot}}}{220\frac{\text{km}}{\text{s}}}\right) \quad (1)$$

where v_{rot} is the rotation velocity of the galaxy and $j_{\max}$ is a parameter with a specific value for each halo. For large n, $a_n \propto 1/n$. Eq. 1 is predicted by the self-similar infall model [10,11] of galactic halo formation. $j_{\max}$ is then the maximum of the dimensionless angular momentum j-distribution [11]. The self-similar model depends upon a parameter ϵ [10]. In CDM theories of large scale

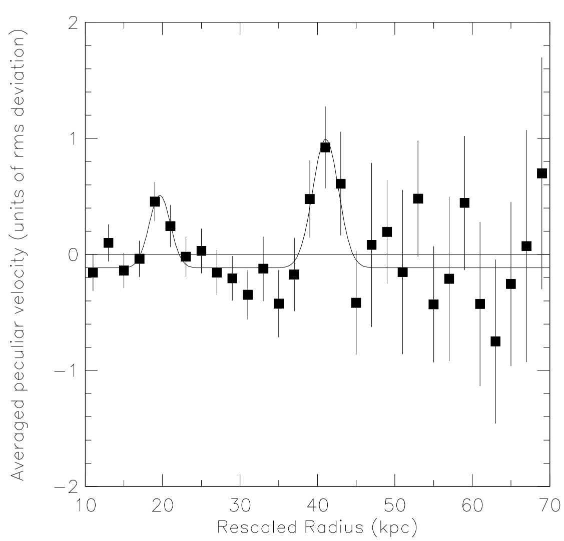

Fig. 1. Composite rotation curve constructed in ref. [12]. It combines data on 32 exterior galaxies to test the hypothesis that the caustic ring radii are given by Eq. (1).

structure formation, ϵ is expected to be in the range 0.2 to 0.35 [11]. Eq. 1 is for $\epsilon = 0.3$. However, in the range $0.2 < \epsilon < 0.35$, the ratios a_n/a_1 are almost independent of ϵ. When $j_{\max}$ values are quoted below, $\epsilon = 0.3$ and $h = 0.7$ will be assumed.

It was pointed out in ref. [11] that including angular momentum in the self-similar infall model results in a depletion of the inner halo and hence an effective core radius. The average amount of angular momentum of the Milky Way halo was estimated [11] by requiring that approximately half of the rotation velocity squared at our location is due to dark matter, the other half being due to ordinary matter. This yields $\bar{j} \sim 0.2$ where $\bar{j}$ is the average of the j-distribution for our halo. $\bar{j}$ and $j_{\max}$ are related if some assumption is made about the shape of the j-distribution. For example, if the j-distribution is taken to be that of a rigidly rotating sphere, one has $j_{\max} = \frac{4}{\pi}\bar{j}$. Hence $j_{\max} \sim 0.25$ for our halo.

Since caustic rings lie close to the galactic plane, they cause bumps in the rotation curve, at the locations of the rings. In ref. [12] a set of 32 extended well-measured rotation curves was analyzed and statistical evidence was found for the $n = 1$ and $n = 2$ caustic rings, distributed according to Eq. 1. In this analysis, each of the 32 individual galactic rotation curves was rescaled according to

$$r \rightarrow \tilde{r} = r \left(\frac{220 \text{ km/s}}{v_{\text{rot}}} \right) \tag{2}$$

where v_{rot} is the measured rotation velocity. To isolate the outer halo-dominated portion of the rotation curves, all data with rescaled radii $\tilde{r} < 10$ kpc were removed. Each rotation curve was then fitted to a line or a quadratic polynomial. The residual deviations were normalized to the rms deviation in each fit and then binned together. The result is the composite rotation shown in Fig. 1 for the case where the individual rotation curves were fitted to quadratic polynomials. The composite rotation curve has two peaks, near 20 kpc and 40 kpc, with statistical significance of 3σ and 2.6σ respectively. It implies that the $j_{\max}$ distribution is peaked near 0.27. The rotation curve of NGC3198, one of the best measured, by itself shows three faint bumps which are consistent with Eq. 1 and $j_{\max} = 0.28$ [4]. Also our earlier estimate of $j_{\max}$ for the Milky Way halo is close to the peak value of 0.27.

3 Evidence for Ring Caustics in the Milky Way

Eq. 1 with $j_{\max} = 0.25$ implies that our halo has caustic rings with radii near 40 kpc/n, where n is an integer. Here we point to evidence in support of this extraordinary claim.

It was already mentioned that the recently discovered ring of stars at $r = 20$ kpc may be interpreted as baryonic matter accreted onto the $n = 2$ caustic ring of dark matter. This interpretation accounts for the 20 kpc radius of the ring as well as for its location in the galactic plane. The spatial coincidence of the 20 kpc ring of stars with the predicted $n = 2$ caustic ring may, of course, be fortuitous. So it is natural to ask whether there is similar evidence for any of the

other caustic rings. The answer is yes for the $n = 3$ ring. Binney and Dehnen studied [13] the outer rotation curve of the Milky Way and concluded that its anomalous behavior can be explained if most of the tracers of the rotation are concentrated in a ring of radius 1.6 $r_\odot$ where $r_\odot$ is our distance to the galactic center. Throughout this paper we use the standard value $r_\odot = 8.5$ kpc. That value is assumed in Eq. 1, and also in refs. [1,2]. The Binney and Dehnen ring is therefore at 13.6 kpc, which is very close to the predicted radius of the $n = 3$ caustic ring. Moreover, there is independent evidence for the existence of the Binney and Dehnen ring.

Olling and Merrifield have recently published [14] a rotation curve for the Milky Way. It is reproduced in Fig. 2. It shows a significant rise between 12.7 and 13.7 kpc. The increase in rotation velocity is 27%, from 220 to 280 km/s. A ring of matter in the Galactic plane produces a rise the rotation curve. The rise expected from the $n = 3$ caustic ring of dark matter, by itself, is only of order 3%. However, the effect of a caustic ring of dark matter is amplified by the ordinary matter (stars, gas, dust ..) which it attracts gravitationally. The amplification would have to be by a factor of order nine in the case of the $n = 3$ ring. One may think, at first, that such as a large amplification is implausible because the back reaction of the ring of ordinary matter upon the caustic ring of dark matter would determine the position of the latter, instead of the latter determining the position of the former. However this is not so because the dark matter caustic is not an overdensity of particles which are at rest with respect to the caustic ring. The particles which at a given time make up the caustic ring are moving with great speed, of order 360 km/s for $n = 3$, and are continually replaced by new particles. As a result, the position of the caustic ring is insensitive to the gravitational field of the matter it attracts.

The existence of rings of ordinary matter precisely where the $n = 2$ and $n = 3$ rings of dark matter are predicted may yet be fortuitous. Fig. 1 does not show a significant rise near the predicted location (10 kpc) of the $n = 4$ caustic ring. Note however that the error bars in Fig. 1 are very large for $r > r_\odot$. The rise near 10 kpc, if indeed there is one, may be too small to show up in the data. On the other hand, the inner ($r < r_\odot$) part of the rotation curve is far better measured, and we may go look for rises there.

Galactic rotation curves are obtained from HI and CO surveys of the Galactic plane. A list of surveys performed to date is given in ref. [15]. Everything else being equal, CO surveys have far better angular resolution than HI surveys because their wavelength is nearly two orders of magnitude smaller (0.26 cm vs. 21 cm). The most detailed inner Galactic rotation curve appears to be that obtained [16] from the Massachusetts-Stony Brook North Galactic Plane CO survey [17]. It is reproduced in Fig. 3. It shows highly significant rises between 3 and 8.5 kpc. Eq. 1 predicts ten caustic rings between 3 and 8.5 kpc. Allowing for ambiguities in identifying rises, the number of rises in the rotation curve between 3 and 8.5 kpc is in fact approximately ten. Below 3 kpc the predicted rises are so closely spaced that they are unlikely to be resolved in the data.

Table I lists ten rises, identified by the radius r_1 where they start, the radius r_2 where they end, and the increase Δv in rotation velocity. The rises are marked as slanted line segments in Fig. 3. The evidence for the rise between 7.30 and 7.42 kpc is relatively weak, so the corresponding numbers are in parenthesis in the Table.

The effect of a caustic ring in the plane of a galaxy upon its rotation curve was analyzed in ref. [7]. The caustic ring produces a rise in the rotation curve which starts at $r_1 = a_n$, where a_n is the caustic ring radius, and which ends a $r_2 = a_n + p_n$, where p_n is the caustic ring width. The ring widths depend in a complicated way on the velocity distribution of the infalling dark matter at last turnaround [7] and are not predicted by the model. They also need not be constant along the ring.

In the past, rises (or bumps) in galactic rotation curves have been interpreted as due to the presence of spiral arms [18]. Spiral arms may in fact cause some of the rises in rotation curves. This does not, however, exclude the possibility of other valid explanations. Two properties of the high resolution rotation curve of Fig. 3 favor the interpretation that its rises are caused by caustic rings of dark matter. First, there are of order ten rises in the range of radii covered (3 to 8.5 kpc). This agrees qualitatively with the predicted number of caustic rings, whereas only three spiral arms are known in that range: Scutum, Sagittarius and Local. Second, the rises are sharp transitions in the rotation curve, both where

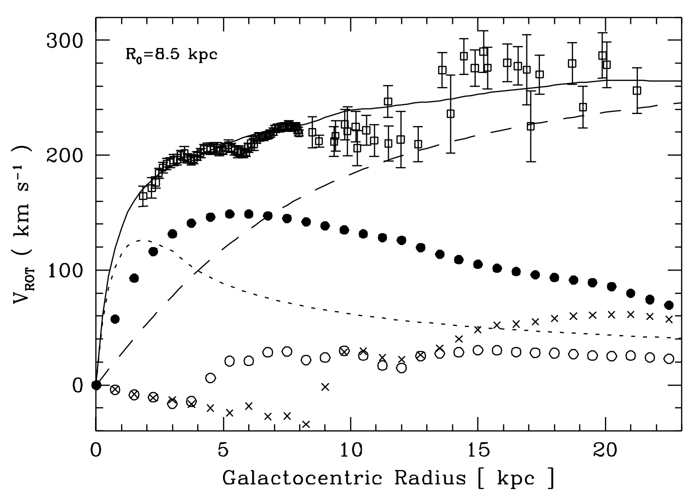

Fig. 2. Milky Way rotation curve from ref. [14]. The different lines represent the contributions from the bulge (dotted), the stellar disk (filled circles), the HI layer (crosses), the H_2 layer (circles), and from a smooth dark halo (dashed). The full line represents the sum of the contributions. Reprinted by permission of the authors and Blackwell Publishing Ltd.

they start (r_1) and where they end (r_2). Sharp transitions are consistent with caustic rings because the latter have divergent density at $r_1 = a$ and $r_2 = a + p$ in the limit of vanishing velocity dispersion. Finally, there are bumps and rises in rotation curves measured at galactocentric distances much larger than the disk radius, where no spiral arms are seen. In particular, the features found in the composite rotation curve of Fig. 1 are at distances 20 kpc and 40 kpc when scaled to our own galaxy.

The self-similar infall model prediction for the caustic ring radii, Eq. 1, was fitted to the eight rises between 3 and 7 kpc by minimizing $rmsd \equiv [\frac{1}{8}\sum_{n=7}^{14}(1 - \frac{a_n}{r_{1n}})^2]^{\frac{1}{2}}$ with respect to $j_{\max}$, for $\epsilon = 0.30$. The fit yields $j_{\max} = 0.263$ and $rmsd = 3.1\%$. The fourth column of Table I shows the corresponding caustic ring radii a_n. In Fig. 3 the latter are indicated by short vertical line segments.

The velocity increase due to a caustic ring is given by

$$\Delta v_n = v_{\rm rot} f_n \frac{\Delta I(\zeta_n)}{\cos\delta_n(0) + \phi'_n(0)\sin\delta_n(0)} \ . \qquad (3)$$

The f_n, defined in ref. [4], are predicted by the self-similar infall model, but $\Delta I(\zeta_n), \delta_n(0)$ and $\phi'_n(0)$, defined in ref. [7], are not. Like the p_n, the latter parameters depend in a complicated way on the velocity distribution of the dark matter at last turnaround. On the basis of the discussion in ref. [7], the ratio on

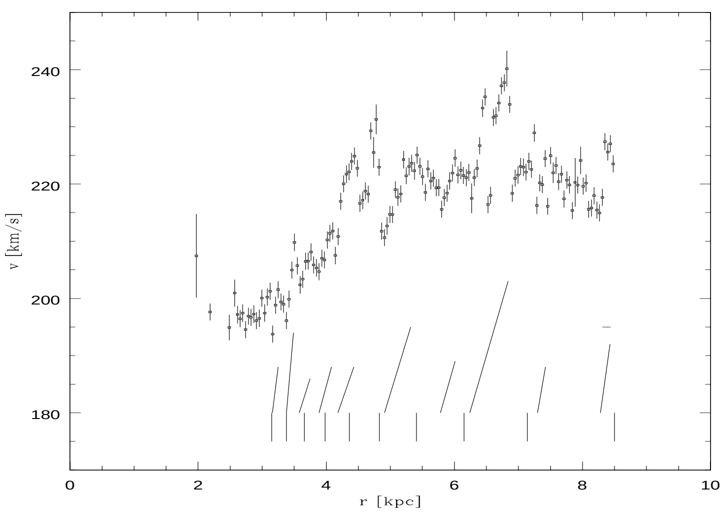

Fig. 3. North Galactic rotation curve from ref. [16]. The locations of the rises listed in the first three columns of Table I are indicated by line segments parallel to the rises but shifted downwards. The caustic ring radii for the fit described in the text are shown as vertical line segments. The position of the triangular feature in the IRAS map of the galactic plane near 80° longitude is shown by the short horizontal line segment. It coincides with a rise in the rotation curve.

Table 1. Radii at which rises in the Milky Way rotation curve of Fig. 3 start (r_1) and end (r_2), the corresponding increases in velocity Δv, the caustic ring radii a_n of the self-similar infall model for the fit described in the text, and typical velocity increases $\bar{\Delta} v_n$ predicted by the model without amplification due to accretion of ordinary matter onto the caustic rings.

r_1 (kpc)	r_2 (kpc)	Δv (km/s)	a_n (kpc) n = 1 ..14	$\bar{\Delta} v_n$ (km/s) n = 1 .. 14
			41.2	26.5
			20.5	10.6
			13.9	6.8
			10.5	5.0
8.28	8.43	12	8.50	3.9
(7.30)	(7.42)	(8)	7.14	3.2
6.24	6.84	23	6.15	2.6
5.78	6.01	9	5.41	2.3
4.91	5.32	15	4.83	2.0
4.18	4.43	8	4.36	1.7
3.89	4.08	8	3.98	1.5
3.58	3.75	6	3.66	1.3
3.38	3.49	14	3.38	1.2
3.16	3.25	8	3.15	1.1

the RHS of Eq. 3 is expected to be of order one, but to vary from one caustic ring to the next. The size of these fluctuations is easily a factor two, up or down. The fifth column of Table I shows Δv_n with the fluctuating ratio set equal to one, i.e. $\bar{\Delta} v_n \equiv f_n v_{\rm rot}$.

For the reasons just stated, the fact that the observed Δv fluctuate by a factor of order 2 from one rise to the next is consistent with the interpretation that the rises are due to caustic rings. However the observed Δv (column 3) are typically a factor 5 larger than the velocity increases expected from the caustic rings acting alone (column 5). This is similar to what we found for the $n = 3$ caustic ring, and suggests that the effects of the $n = 5...14$ caustic rings are also amplified by baryonic matter they have accreted. I'll argue that the gas in the disk has sufficiently high density and low velocity dispersion to produce such large amplification factors. I'll also give observational evidence in support of the hypothesis.

The equilibrium distribution of gas is:

$$d_{\rm gas}(\boldsymbol{r}) = d_{\rm gas}(\boldsymbol{r}_0)\exp[-\frac{3}{< v_{\rm gas}^2 >}(\phi(\boldsymbol{r}) - \phi(\boldsymbol{r}_0))] \ , \qquad (4)$$

where d is density and ϕ gravitational potential. In the solar neighborhood, $d_{\rm gas} \simeq 3\cdot 10^{-24}\frac{\rm gr}{\rm cm^3}$ [19], which is comparable to the density of dark matter inside the tubes of caustic rings near us. From the scale height of the gas [19] and the assumption that it is in equilibrium with itself and the other disk components, I estimate $\langle v_{\rm gas}^2\rangle^{\frac{1}{2}} \simeq 8$ km/s. The variation in the gravitational potential due to a caustic ring over the size of the tube is of order $\Delta\phi_{\rm CR} \simeq 2fv_{\rm rot}^2 p/a \simeq (5\frac{\rm km}{\rm s})^2$. Because $\frac{3}{<v_{\rm gas}^2>}\Delta\phi_{\rm CR}$ is of order one, the caustic rings have a large effect on the distribution of gas in the disk. The accreted gas amplifies and can dominate the effect of the caustic rings on the rotation curve. To check whether this hypothesis is consistent with the shape of the rises would require detailed modeling, as well as detailed knowledge on how the rotation curve is measured. However, there is observational evidence in support of the hypothesis.

The accreted gas may reveal the location of caustic rings in maps of the sky. Looking tangentially to a ring caustic from a vantage point in the plane of the ring, one may recognize the tricusp [7] shape of the D_{-4} catastrophe. I searched for such features. The IRAS map of the galactic disk in the direction of galactic coordinates $(l, b) = (80°, 0°)$ shows a triangular shape which is strikingly reminiscent of the cross-section of a ring caustic. The relevant IRAS maps are posted at http://www.phys.ufl.edu/∼sikivie/triangle/ . They were downloaded from the Skyview Virtual Observatory (http://skyview.gsfc.nasa.gov/). The vertices of the triangle are at $(l, b) = (83.5°, 0.4°), (77.8°, 3.4°)$ and $(77.8°, -2.6°)$. The shape is correctly oriented with respect to the galactic plane and the galactic center. To an extraordinary degree of accuracy it is an isosceles triangle with axis of symmetry parallel to the galactic plane, as is expected for a caustic ring whose transverse dimensions are small compared to its radius. Moreover its position is consistent with the position of a rise in the rotation curve, the one between 8.28 and 8.43 kpc ($n = 5$). The caustic ring radius implied by the image is 8.31 kpc and its dimensions are $p \sim 130$ pc and $q \sim 200$ pc, in the directions parallel and perpendicular to the galactic plane respectively. It therefore predicts a rise which starts at 8.31 kpc and ends at 8.44 kpc, just where a rise is observed. The probability that the coincidence in position of the triangular shape with a rise in the rotation curve is fortuitous is less than 10^{-3}.

In principle, the feature at $(80°, 0°)$ should be matched by another in the opposite tangent direction to the nearby ring caustic, at approximately $(-80°, 0°)$. Although there is a plausible feature there, it is much less compelling than the one in the $(+80°, 0°)$ direction. There are several reasons why it may not appear as strongly. One is that the $(+80°, 0°)$ feature is in the middle of the Local spiral arm, whose stellar activity enhances the local gas and dust emissivity, whereas the $(-80°, 0°)$ feature is not so favorably located. Another is that the ring caustic in the $(+80°, 0°)$ direction has unusually small dimensions. This may make

it more visible by increasing its contrast with the background. In the $(-80°, 0°)$ direction, the nearby ring caustic may have larger transverse dimensions.

4 The Big Flow

Our proximity to a caustic ring means that the corresponding flows, i.e. the flows in which the caustic occurs, contribute very importantly to the local dark matter density. Using the results of refs. [4,7,11], we can estimate their densities and velocity vectors. Let us assume, for illustrative purposes, that we are in the plane of the nearby caustic and that its outward cusp is 55 pc away from us, i.e. $a_5 + p_5 = 8.445$ kpc. The densities and velocity vectors on Earth of the $n = 5$ flows are then:

$$d^+ = 1.7\ 10^{-24}\ \frac{\mathrm{gr}}{\mathrm{cm}^3}\ ,\ d^- = 1.5\ 10^{-25}\ \frac{\mathrm{gr}}{\mathrm{cm}^3}\ ,\ \boldsymbol{v}^\pm = (470\ \hat{\phi} \pm\ 100\ \hat{r})\ \frac{\mathrm{km}}{\mathrm{s}}, \quad (5)$$

where $\hat{r}, \hat{\phi}$ and $\hat{z}$ are the local unit vectors in galactocentric cylindrical coordinates. $\hat{\phi}$ is in the direction of galactic rotation. The velocities are given in the (non-rotating) rest frame of the Galaxy. Because of an ambiguity, it is not presently possible to say whether $d^\pm$ are the densities of the flows with velocity $\boldsymbol{v}^\pm$ or $\boldsymbol{v}^\mp$. The large size of d^+ is due to our proximity to the outward cusp of the nearby caustic. Its exact value is sensitive to our distance to the cusp. We do not know that distance well enough to estimate d^+ with accuracy. However we can say that d^+ is very large, of order the value given in Eq. 5, perhaps even larger. If we are inside the tube of the nearby caustic, there are two additional flows on Earth, aside from those given in Eq. 5. A list of local densities and velocity vectors for the $n \neq 5$ flows can be found in ref. [20]. An updated list is in preparation.

Eq. 5 has dramatic implications for dark matter searches. Previous estimates of the local dark matter density, based on isothermal halo profiles, range from 5 to 7.5 $10^{-25}\ \frac{\mathrm{gr}}{\mathrm{cm}^3}$. The present analysis implies that a single flow (d^+) has of order three times (or more) that much local density.

The sharpness of the rises in the rotation curve and of the triangular feature in the IRAS map implies an upper limit on the velocity dispersion δv_{DM} of the infalling dark matter. Caustic ring singularities are spread over a distance of order $\delta a \simeq \frac{R\ \delta v_{\mathrm{DM}}}{v}$ where v is the velocity of the particles in the caustic, δv_{DM} is their velocity dispersion, and R is their turnaround radius. The sharpness of the IRAS feature implies that its edges are spread over $\delta a \lesssim 20$ pc. Assuming that the feature is due to the $n = 5$ ring caustic, $R \simeq 180$ kpc and $v \simeq 480$ km/s. Therefore $\delta v_{\mathrm{DM}} \lesssim 53$ m/s. This bound is strongly at odds with the often quoted claim that structure formation on small scales causes all, or nearly all, late infalling dark matter to be in dwarf galaxy type clumps, with velocity dispersion of order 10 km/s.

The caustic ring model may explain the puzzling persistence of galactic disk warps [21]. These may be due to outer caustic rings lying somewhat outside the galactic plane and attracting visible matter. The resulting disk warps would not

damp away, as is the case in more conventional explanations of the origin of the warps, but would persist on cosmological time scales.

The caustic ring model, and more specifically the prediction Eq. 5 of the locally dominant flow associated with the nearby ring, has important consequences for axion dark matter searches [22], the annual modulation [20,23,24,25] and signal anisotropy [26,24] in WIMP searches, the search for γ-rays from dark matter annihilation [27], and the search for gravitational lensing by dark matter caustics [8,28]. The model makes predictions for each of these approaches to the dark matter problem.

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